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FATIGUE RESISTANCE OF DURALUMIN.

From "Veralagen en Verhandelingen van den Rijks-Studiedienst voor de Luchtvaart" (Amsterdam), 1921, Part I, Report M 17 A.

September, 1922.

FATIGUE RESISTANCE OF DURALUMIN.*

Where, in the following report, mention is made of fatigue, it always refers to the weakening of the material produced by rapidly changing stresses below the limit of elasticity.

The study of this phenomenon is of very great importance for the science of aviation, since the vibrations to which an airplane is subjected during flight may considerably shorten the life of its various parts.

It is known that the data obtained from the most common tests (tensile, shock, bending, compression and the Brinnell or Shore test) furnish no basis for the establishment of dimensions giving absolute guaranty against fatigue. Even with the introduction of the customary factors of safety, the admissible stress is often exceeded.**

With the machines built for these tests by the "Gebr. Amsler" (Amsler Brothers) at Schaffhausen and the "Aktiebolaget Alpha" at Stockholm, the alternating stress was obtained by a test bar which was firmly held at one end and subjected to rotation. To a pulley A (Fig. 1), running on ball bearings and driven by a motor M, there is firmly attached a threaded holder B, into

* From "Verslagen en Verhandelingen van den Rijks-Studiedienst voor de Luchtvaart" (Amsterdam), 1921, Part I, Report M 17A, pp. 162-172.

** The technical importance of such tests is evident from the fact that, according to the Journal of the Institute of Metals (1920), in America, a systematic investigation of these fatigue phenomena has been begun by the National Research Council, in cooperation with the University of Illinois, for which $51,000 per year for two years was made available.

which the test rod is screwed. The latter carries on its left outer end a self-adjusting ball-bearing, with a band D, a spring E and a weight F (see also Fig. 2). The test rod was given a speed of 1100 r.p.m. by the motor M.

The machine of the Alpha Company has room for two test rods, which can both be tested at the same time, the instant of breaking of each being indicated by a special device. This machine has a speed of 2800 r.p.m. The outer part of the test rod, between the point F and the beginning of the fillet at A (Fig. 3) is subjected to a rapidly alternating tension and compression, from which may be easily calculated the value of $\rho = M : W$, which has a sinusoidal curve. The tension is always kept below the elastic limit and hence no changes in shape occur, such as take place when the limit is exceeded. The number of revolutions before the occurrence of a break constitutes a measure of the resistance of the substance tested to the given alternating stress.

The prime requisite for a successful test is the smooth running of the machine. Secondary vibrations may make the actual stress much greater than the calculated, thereby rendering the result worthless. Although an absolutely smooth running of the machine is unattainable, the vibrations may become so small that their influence can probably be disregarded. For this purpose, various modifications of the original Amsler machine appear neces sary.

As regards the breaking of a rod subjected to very great stresses, it may be noted that, above a certain revolution speed, the cohesion of the substance is disturbed. Near the surface, which in this case is most heavily stressed, there occur, in or between the crystals, microscopic cracks which, under continued stress, increase in number and finally combine.

At the bottom of the crack, the local stress increases and the crack goes deeper. As soon as the stress becomes too great in the remaining part, the rod breaks. In the Amsler machine, the weight F falls several centimeters and releases the pawl P, thereby breaking the circuit and stopping the motor.

The holder B, operates the tachometer T, so that the latter is also stopped automatically.

The first part of the break can always be distinguished by the smooth, sometimes silk-like, surface. The part of the rod to give way last breaks quicker and shows a coarser structure.

Fig. 4 shows the breaks of two test rods and also another rod which was partially broken, but was still strong enough to carry the load. In both breaks there is a clearly defined line between the smoother and rougher portions. That such breaks actually occur in practice is shown by Figs. 5-7.

Fig. 5 shows a break in a connecting rod bolt, which was evidently caused by fatigue.

Fig. 6 shows a break in a coupling bolt from the engine laboratory of the R.S.L. (Rijks-Studiedienst voor de Luchtvaart). This coupling was simply subjected to vibrations. Here also the fatigue crack is very evident.

Fig. 7 shows a bolt for attaching a stay wire to the body of of a Spijker airplane. This bolt broke after 100 hours of flight.

Aside from the magnitude of the stress, two other factors play an important role in fatigue phenomena: namely, the shape and the finish of the structural parts.

As regards the shape, it can be shown that abrupt transitions noticeably diminish the resistance of the smaller part to fatigue. For illustration, the transition from the body to the head of the bolt shown in Fig. 8 is much too sudden. The bolt in Fig. 7 also shows a similar sudden contraction, which doubtless accounts for its breaking after so few hours of flight. Hence the radius of the fillet in Fig. 2 should not be made too small. The influence of the length of r can be determined by repeating the experiment with the same load on the stressed part, but with different fillets. It was thus found that, above a certain value of r, the fillet has no further influence. In the experiments here described, r always had exactly the same value.

The finish of parts subject to fatigue must be smooth and free from scratches. A sharp scratch greatly facilitates the formation of a small crack, thereby increasing the danger of a break.

This point is illustrated by Fig. 9, which shows a test rod with a small groove, scarcely more than a scratch, outside the critical section. Although the stress was exerted on the bearing section (giving a shorter arm for the bending moment), the rod broke there from fatigue, after a too small number of revolutions for the given load. As evidence that this is regarded in foreign countries as very important in airplane building, it is expressly stated in the "British Standard Aircraft Material Specifications" that all transverse grooves on the inside of hollow parts must be carefully removed.

Fig. 3 shows the shape and dimensions of a test rod. In the first tests, much larger rods were used, as shown in Fig. 9. The smaller dimensions were afterwards chosen, in order to enable the taking of test pieces from small airplane parts. Besides, it does not take so long to test small rods. In screwing the test rod into the holder, care must always be taken to do it with a sharp instrument and small "chisel-pressure," so as to avoid injury to the material as much as possible.

The fillet at A is turned with a gauge held exactly in the direction of the radius r. After turning, all scratches are carefully removed. Where the outcome of the test is affected by the shape and size of the fillet, the resulting data apply only to rods with the given fillet. In continuing the investigation, it will b endeavored to determine how the results are affected by changing the radius of the fillet.

The following points are of practical importance in a methodical investigation.

1. Relation, for different metals, between the value of the intermittent stress and the length of life of the part or test rod. In this connection, data may be gathered with reference to the admissible load.

2. Relation between fatigue resistance and the treatment un-

dergone by the metal (whether cold-worked, annealed, hardened, c. refined).

3. Relation between fatigue resistance and the various physical and chemical properties of the substance.

4. Determination of whether a substance is more or less fatigued and whether there is any incipient break.

5. Discovery of remedies for incipient and confirmed fatigue.

6. Studying the effect of periods of rest on the state of fatigue.

7. Studying fatigue phenomena in different kinds of joints.

8. Influence of form and finish of different parts on fatigue resistance.

All these points must be studied under alternating tension and compression, torsion and combinations of two or more kinds of stress, while the changing of the stress, both from maximum to minimum and from zero to maximum, must also receive attention.

Although nothing but metal tests have thus far been mentioned, the above program may also be applied to wood, fabric, glue, varnish, etc.

From the scientific point of view, it is also of interest to study:

9. Effect of alternating tension and compression on inner structure of material.

10. Connection between fatigue and elasticity phenomena.

A number of scientists have experimented in this field. Aft the fundamental tests of Wöhler: "Versuche zum Messen der Biegung und Verdrehung von Eisenbahnwagen-Achsen wahrend der Fahrt (Experiments in Measuring the Bending and Twisting of Railway Car Axles while Running), Zeitschrift für Bauwesen, 1858, p.642, and "Über die Festigkeitsversuche mit Eisen und Stahl" (Strength Tests with Iron and Steel), Z. f. Bauwesen, 1870, and of Spangenberg: "Über das Verhalten der Metalle bei wiederholten Anstrengungen" (Effect of Repeated Stresses on Metals), 1875, Bauschinger, Martens and other scientists have continued these experiments. More recently very valuable experiments have been tried by Englishmen and, at the same time, the formation of cracks has been studied with the aid of the microscope. For the literature up to 1912, reference can be made to Boeke: "Over breuk na herhaalde belasting" (Concerning Breaks after Repeated Stressing), Brusse, Rotterdam, 1914.

A list of documents published since then is given in Appendix 2 of this article.

The object of the experiments now being carried on by the Rijks-Studiedienst is to obtain data:

a) Concerning the fatigue curves of a few duralumin samples, in consequence of the constantly increasing use of this metal in airplanes.

b) Concerning the effect of various thermal processes on the fatigue resistance of a suitable kind of cast iron.

The two different kinds of duralumin tested (z and 681 B) were made for the Rijks-Studiedienst by the Durener Metallwerke.

By duralumin (an alloy discovered by Alfred Wilm in the "Centralstelle für wissenschaftlichtechnische Untersuchungen" (Centr Institute for Scientific and Technical Investigations) at Neubabelsberg (1903-1911) and of which the Dürener Metallwerke at Düren is the patentee and original manufacturer) is understood a substance containing:

Copper,	3.5 to 5.5 %
Manganese,	0.5 " 0.8 %
Magnesium,	0.5 % and
Aluminum, the remainder,	

excepting for small quantities of iron, silicon and lead, always present as impurities.

The most important properties of duralumin are as follows:

Specific gravity, 2.78 to 2.83, according to composition.

Melting point, about 665°C.

Tensile strength of cast metal, 18-20 kg. per sq.mm. with an elongation of 7 to 10%;

Tensile strength of cast metal, which has afterwards been refined, 28-30 kg. per sq.mm., with an elongation of 15 to 20 %; tensile strength of wrought and afterwards refined metal, 35-50 kg. per sq.mm., with an elongation of 12 to 22 %.* These figures simply indicate the approximate limits.

The metal employed in our experiments was furnished by the Dürener Metallwerke in the form of cylindrical rods of 20 mm. diameter. It was questioned whether it would not be better to experi-

* Alfred Wilm, "Physikalisch-technische Untersuchen uber Magnesiumhaltige Aluminium Legierungen," Metallurgie, 1911, p.225.

ment with thin flat bars, since they are chiefly used in practice but it was decided to begin with round specimens, for obtaining general data, and then to pass over to other shapes.

In order to eliminate any possible irregularity of structure in the center of the rod and at the same time to obtain test rods of like dimensions and of the same metal as the fatigue rods, the rods are sawn lengthwise into four similar segments and from these similar segments the test rods are carefully turned. The diameter of each test rod is 5 mm. and its length 25 mm., or five diameters. The following results were obtained.

Alloy hardness 1.	Strength: kg/mm²	Elasticity limit kg/mm²	Elongation % for 5 diameters	Contraction %
Z	45.8	34.4	14.6	33.0
	45.8	35.4	13.3	33.0
	43.4	32.7	14.0	28.5
	43.5	34.6	13.0	31.4
681 B	50.0	42.5	15.0	33.0
	48.4	42.7	14.3	29.4
	49.6	44.0	13.5	37.5
	49.3	41.8	15.1	35.0
	49.6	42.7	17.4	33.9

By chemical analysis the composition of the two alloys was found to be as follows.

Alloy	Z	681 B
Copper	4.50	3.80
Manganese	0.95	0.54
Iron	0.47	0.46
Magnesium	0.51	0.45
Silicon	0.20	0.42
Aluminum	rest	rest

By microscopical investigation it was found that both alloys consisted of crystalline masses of Cu and Al containing $Cu\ Al_2$ in varying proportions. The direction of the grain is plainly indicated by the lay of the copper-containing particles, while the crystals themselves are seen, in the longitudinal section, to be elongated in the direction of the grain (Figs 10, 11, 12).

The preparation and etching of these alloys is not easy and a thorough investigation has been begun, as to the best treatment before the microscopic examination.

In order to make the crystals visible, the preparations are etched in a mixture of;

Alcohol (96%),	85% by volume
Nitrobenzol,	10% " "
Hydrofluoric acid (50%),	5% " "

while, for making the $Cu\ Al_2$ visible, a 20% solution of nitric acid (25%) in water at 70°C is used. The results of the fatigue tests are shown graphically in Fig. 13.

In this connection, it may be remarked that the logarithmic division of the scale of the abscissas employed by some authors in America is not applicable since, in our opinion, there are yet no satisfactory reasons for expecting to obtain thereby any better understanding of the results. It is evident, from a comparison of the values given in Appendix I with Fig. 13, that the points found for the Z and B alloys can be represented by the same line.

Most of the rods broke with the normal characteristic fatigue break at the point of greatest stress. In a few instances the break was irregular, while in others the break was normal, but further from the point of application of the weight, than was consistent with the shape of the test rod. Where, in the latter case, the rod broke in a thicker part of the fillet, it may be assumed that there was some abnormality or other in the metal. In order to have only reliable data for the calculations, the results obtained from rods which broke more than 0.3 mm. from the beginning of the fillet were not used in the graphic representations.

It is comprehensible that, as soon as the field is approached where the line runs nearly horizontal in the graphic representation, the number of revolutions can vary greatly for a given load. Thus the points 3, 25, 9, 7 and 20 lie on the same stress line. Under this stress, a slight variation in the metal or in the finish of the test rod exerts a great influence on how soon the first crack occurs and thus on the total number of revolutions. In accurate work, a great number of points must be found in this region. Thus the lower limit is not a definite line but a certain boundary field, the width of which varies with the accuracy of the tests and the degree of uniformity of the metal.

Point 20 belongs still much farther to the right than it is marked, since the rod was not broken in this test after thirty million alternations. The same is true of point 6, as the rod was not broken after fifteen million alternations. In connection with the different kinds of duralumin tested, the location of the lowest horizontal line is noticeable, which, in this case, for rods of the 681B variety, lies at 30% of the breaking strength and 35% of the limit of elasticity, while the corresponding numbers for the Z variety are respectively 33% and 44%.

For cast iron rods similarly tested in the crude, annealed, hardened and refined conditions, this limit was much higher (80% of the corresponding limit of elasticity). The series of tests with cast iron could not be finished in time for this report.

It is intended to continue the tests with duralumin and other light alloys in another form (flat) and also to investigate the effect of various thermal processes on fatigue resistance.

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Appendix 1.

Load kg/mm²	Test Rod No.	Revolutions before breaking.	Alloy	Distance of break from normal point in mm	Remarks.
37.2	1	3,670	Z	0.1	Not used in graphic.
29.8	2	13,730	Z	0.1	"
27.5	19	21,700	Z	---	Rough break, not used in graphic.
24.2	39	49,800	B	---	"
22.5	15	153,700	Z	0.5	Abnormal break.
22.5	17	587,400	Z	0.5	"
22.5	18	152,500	Z	0.5	Break rough.
22.4	38	59,700	B	0.4	Break rough.
22	4	177,130	Z	---	" "
22	37	259,320	B	---	" "
20.6	22	122,300	Z	---	Indistinct break,
19.8	34	419,850	B	---	not used in graphi..
19.2	24	178,660	B	0.6	Normal break.
19.1	13	297,600	Z	0.4	Abnormal break.
18.9	12	222,610	Z	0.2	" "
18.7	11	232,490	Z	---	" "
18.2	40	618,180	B	---	" "
18.1	32	2,904,000	B	0.6	Normal break
17.7	23	707,100	Z	0.8	Nearly normal break.
17.6	31	762,240	B	---	" " "
17.6	33	336,200	B	---	" " "
17.2	36	570,900	B	0.2	" " "
17	29	3,036,000	B	---	" " "
16.7	10	1,423,250	Z	0.3	" " "
16.5	3	825,860	Z	---	" " "
16.5	7	7,456,090	Z	---	" " "
16.5	9	1,638,140	Z	---	" " "
16.5	20	27,500,000	Z	---	Abnormal break.
16.5	25	1,003,680	B	---	" "
16.4	28	1,403,540	B	0.6	Normal break.
16.1	26	976,260	B	0.2	" "
16	27	8,568,000	B	0.1	" "
15.7	14	957,230	Z	0.5	Complete break.
15.4	6	15,000,000	Z	---	Not broken.
15.4	16	11,000,000	Z	---	" "
14.4	5	10,000,000	Z	0.1	" "

Translated by National Advisory Committee for Aeronautics.

Report M 17A. Appendix 2.

Bibliography after 1912.

ROGERS. So-called crystallization through fatigue J. Ir. St. Inst. 1913. II. 392.

NUSSBAUMER. Etude comparative sur les essais au choc simple, les essais aux chocs répétés, les essais de flexion rotative et les essais de flexion alternée. Rev. Met. Mém. XI. 1914. 1133.

MARTENS. Mitt. Kgl. Marter. Prüf. amt I. 1914.

PREUSZ. Kerbwirkung bei Dauerbeanspruchung. Zeitsch. Ver. d. Ing. 1914. I. 701.

ROWETT. Elastic hysteresis of steel. Proc. Royal Soc. (J. Ir. St. Inst. 1914. II. 366).

STROMEIJER. Fatigue of metals. Proc. Royal Soc. (J. Ir. St. Inst. 1914. II. 366).

SMITH & WEDGWOOD. Stress-strain loops for steel in the cyclic state. J. Ir. St. Inst. 1915. I. 365.

MOORE & SEELY. Am. Soc. test. Mat. (St. u. E. 1915. II. 1233).

STANTON & BATSON. On the fatigue resistance of mild steel under various conditions of stress distribution. Enging. 1916. 15 Sept. 269.

POPPLEWELL. The influence of speed on endurance tests. Enging. 1916. 20 Oct. 339.

HAIGH. Endurance of metals under alternating stresses. J. Ir. St. Inst. 1916. I. 373.

MASON. Speed effect and recovery in slow speed alternating stress tests. Proc. Roy. Soc. (J. Ir. St. Inst. 1916 I, 373).

LUDWIK. Ueber die Ermüdung der Metalle. Z. d. Oest. Ing. u. Arch. Ver. 1916. Heft 42.

MASON. On the hysteresis of steel under repeated torsion. Enging. 15 Sept. 1916. 269.

RUDELOFF. Der heutige Stand der Dauerversuche mit Metallen. Verh. Gewerbfl. 1916. VII. (St. u. E. 1917. I. 334).

LEON. Ueber die Ermudung von Maschinenteilen. Zeitschr. Ver. d. Ing. 1917. 196 en 214.

Mc.ADAM. Alternating torsion tests. Am. Soc. Test. Mat. (J. Ir. St. Inst. 1917. II. 437).

BAILEY. Ductile materials under variable shear stress with special reference to shafts subjected to bending and twisting. Enging. 1917. July 27. 81.

PARKER HAIGH. Experiments on the fatigue of brasses. Enging. 1917. Sept. 21. 315.

MASON. Alternating stress experiments. Proc. Inst. Mech. Eng. 1917. (J. Ir. St. Inst. 1918. I. 537).

MOORE & PUTNAM. Effect of cold working on fatigue due to reversed stress. Bull. Am. Inst. Min. Eng. 1919. (J. Ir. St. Inst. 1919. I. 686).

A. STODOLA & F. SCHÜLE. Hohlkehlenscharfe und Dauerbiegung. Schweiz. Bauz. 1918. (St. E. 1918. I. 596).

MOORE & GEHRIG. Some fatigue tests of nickel steel and chrome-nickel steel. Proc. Am. Soc. test. Mat. 1919. II. 206.

GIBSON. Fatigue and impact tests of aluminium alloys. Proc. Am. Soc. Test. Mat. XX. 1920. II. 115.

JENKIN. Report on materials of construction used in aircraft and aircraft engines. 1920. Stationary office.

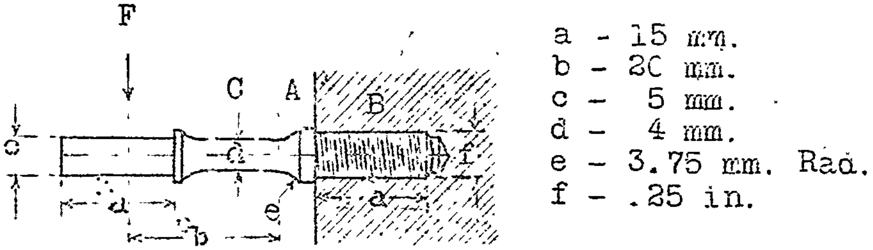
MOORE & KOMMERS. Fatigue of metals under repeated stresses. J. Ir. St. Inst. 1920.

E.P.& E.K. STENGER. Fatigue strength of carbon spring steel. Chem. and Met. Eng. 29/9/20 p.635.

GIBSON. Fatigue and impact fatigue tests of aluminium alloys. Proc. Am.Soc. Test. Mat. (J. Ir. St. Inst. 1921. I. 442).

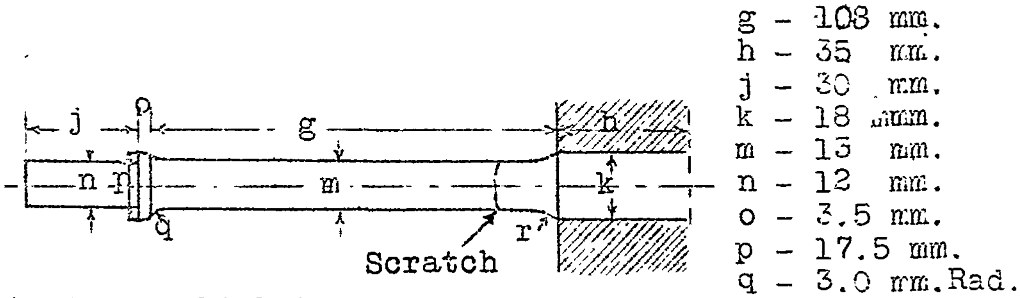
McADAM. A high speed alternatig torsion testing machine. Proc. Am. Soc. Test. Mat. (J. Ir. St. Inst. 1921. I. 448).

Fig. 3.



Small test rods used for tests described in report.

Fig. 9.



Fatigue test rod which had a transverse scratch outside the critical cross-section and broke at that point-(Break is indicated in the figure)

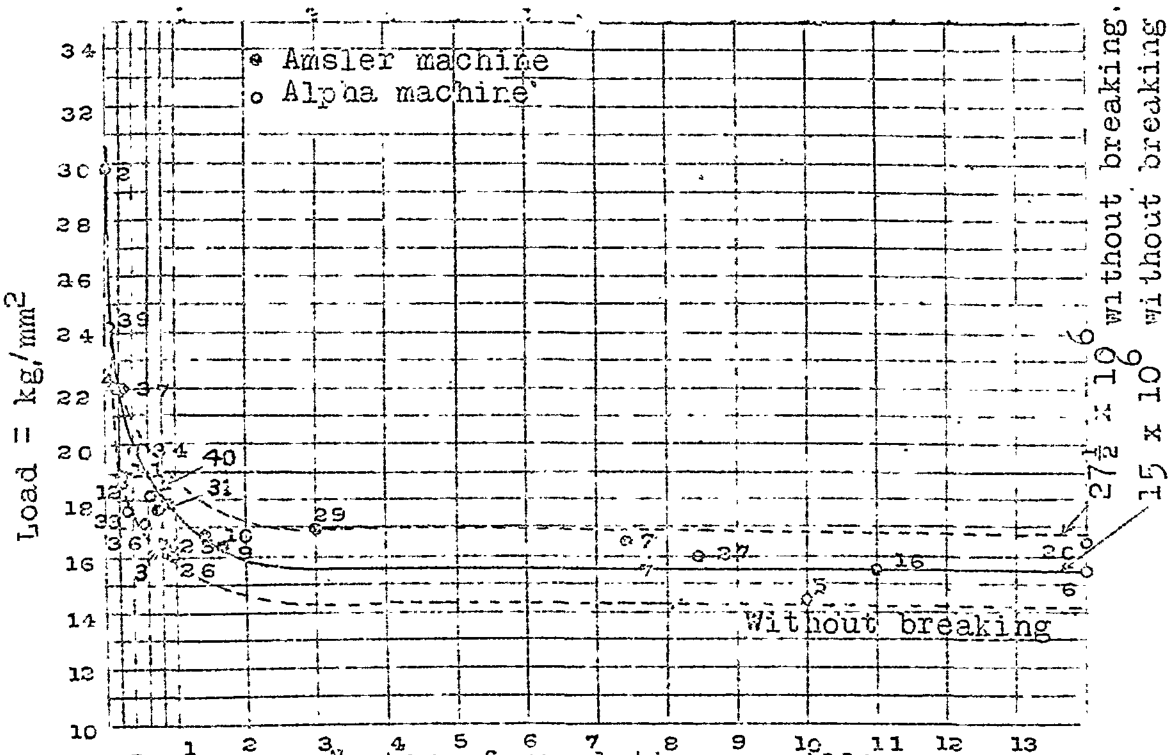


Fig. 13.

Fatigue diagram of duralumin alloys Z and 681B. Although the limits of these alloys seem to be respectively ± 34 & ± 43 kg/mm.

Figs. 3, 9, and 13.

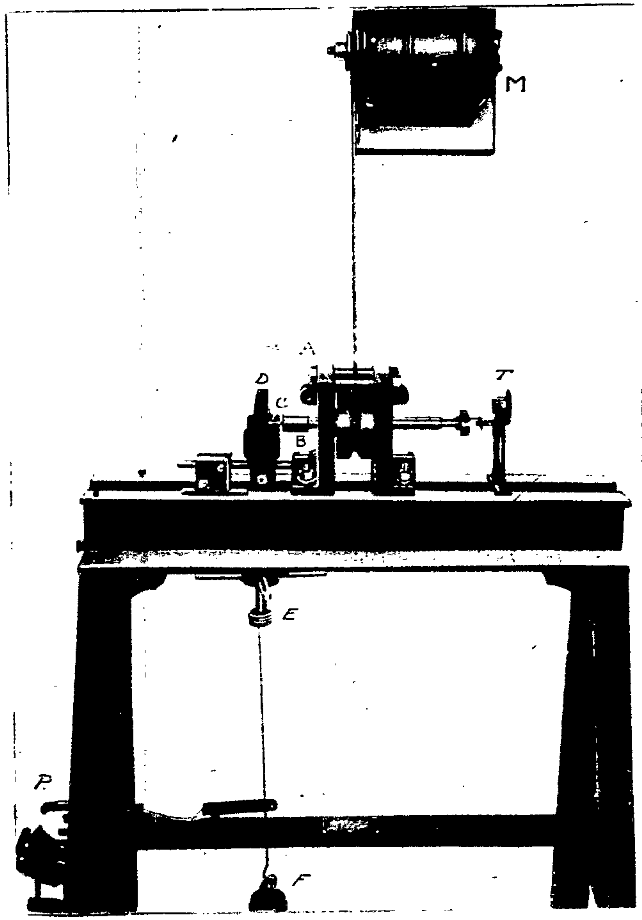


Fig. 1.

Fatigue Testing Machine made by Amsler Bros, Schaffhausen, (1100 r.p.m.).A few modifications were made by the R.S.I.

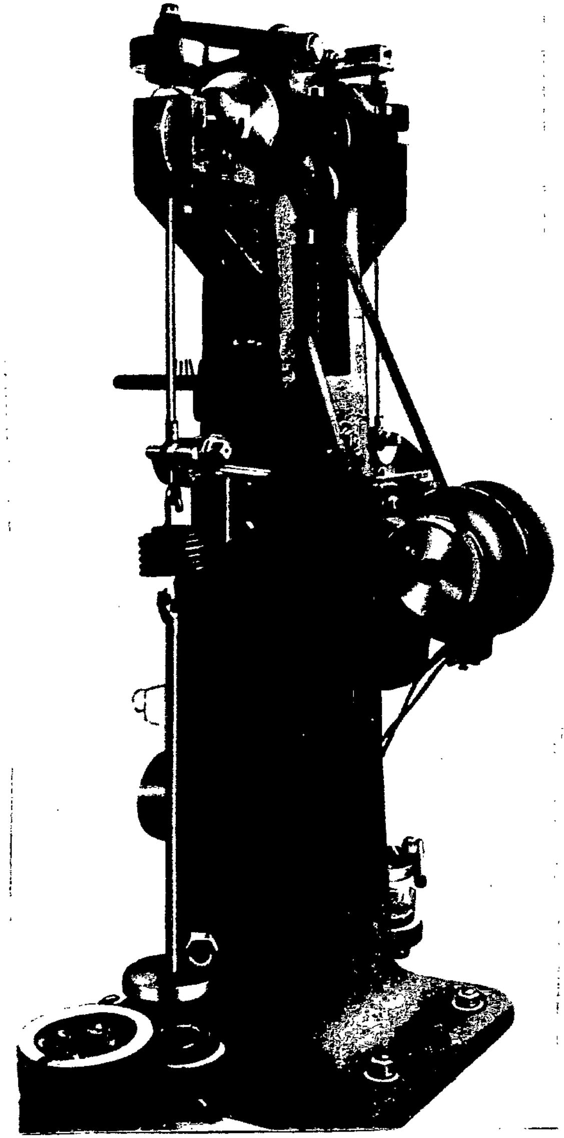


Fig. 2

Fatigue Testing Machine made by Alpha Co., Stockholm (2800 r.p.m.)

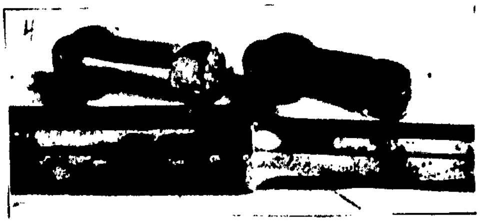


Fig. 4 - Broken rods, tested on Amsler Machine

Fig. 5 - Fatigue break of a $1\frac{1}{4}$" connecting rod bolt from a gasoline engine. The dark upper left hand part shows how far the fatigue crack went before the bolt broke.

Fig. 6 - Fatigue break of a $1\frac{1}{4}$" bolt from an engine coupling. The dark segment at the top indicates the fatigue crack.

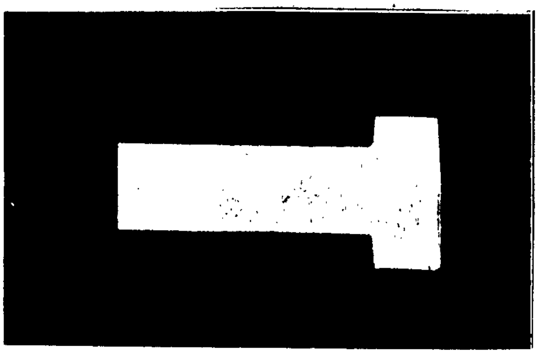


Fig. 8 - Spyker bolt like Fig. 7 (magnified) sawed through in order to show abrupt transition from body to head better.

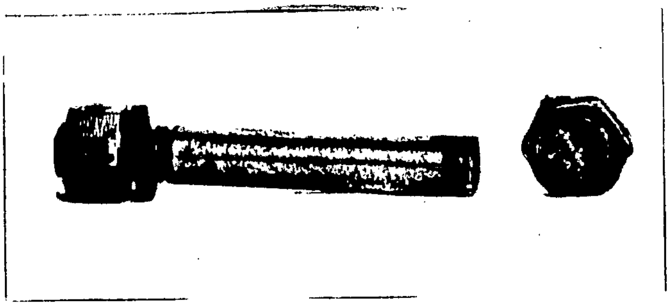


Fig. 7 - Stay wire fastening bolt $\frac{1}{4}$" (from a Spyker airplane) which broke from fatigue after 100 hours of flight. Fatigue crack indicated by dark portion of break.

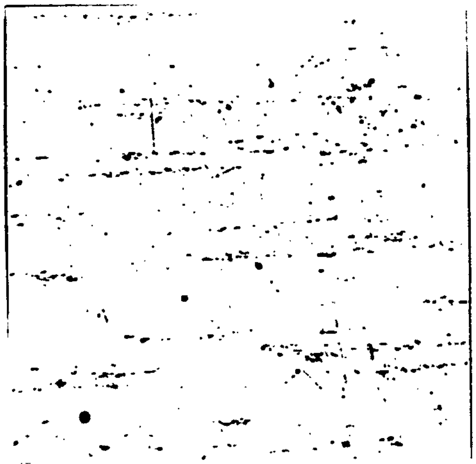


Fig. 10 - Duralumin alloy 681 B, magnified 100 times. Etched with 10% solution of HNO_3 in water at 70°C for 5 sec. The copper aluminate ($Cu\ Al_2$) is darkened by the etching. Direction of grain is plainly visible.

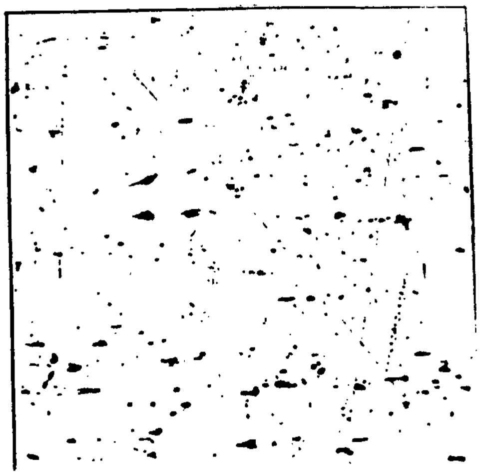


Fig. 11 - Duralumin alloy Z, magnified 100 times. Etched as in Fig.10. The structure of the copper aluminate is coarser here.

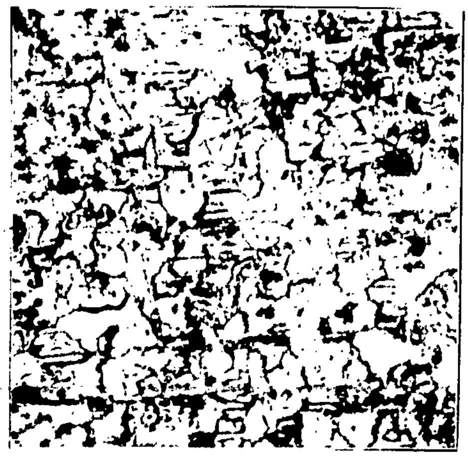


Fig. 12 - Cross section of a duralumin rod, alloy Z. Magnified 200 times. The crystalline masses of aluminum are rendered visible by etching for about 60 sec. in 85% alcohol plus 5% hydrofluoric acid (HF) plus 10% nitro-benzol.